Cosmological Lepton Asymmetry, Primordial Nucleosynthesis, and Sterile Neutrinos

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We study the cosmological lepton number-driven conversion of active neutrinos, to a singlet, "sterile" neutrino species in the post-weak decoupling environment of the early universe. We then assess the impact of this process on Big Bang Nucleosynthesis (BBN) and examine the prospects for reconciling the primordial helium abundance with neutrino mass-squared differences that lie in the range $0.2\ \mathrm{eV}^2 < \delta m^2_{as} < 100\ \mathrm{eV}^2$ by means of a cosmological primordial lepton number. This neutrino mass-squared range is significant because it has been invoked to give a vacuum neutrino oscillation explanation for the Los Alamos Liquid Scintillator Neutrino Detector (LSND) experiment's result, and it is covered by the ongoing mini-BooNE experiment.

A positive signal in mini-BooNE, i.e., confirming the interpretation of the LSND result in terms of vacuum neutrino mixing, sets up an immediate crisis in neutrino physics. Such a result, when combined with the already well established evidence for neutrino mixing at mass-squared differences associated with the atmospheric and solar neutrino anomalies, would suggest the existence of three independent neutrino mass-squared differences which would, in turn, require four neutrino species. Given the Z^0-width limit on the number of flavors of neutrinos with standard weak interactions (3), a fourth neutrino would have to be "sterile," with subweak interaction strength, e.g., perhaps a U(2) singlet.

Hand-in-hand with this particle physics dilemma, evidence for a singlet neutrino that mixes with active neutrinos in this mass-squared range also confronts cosmology with a curious and vexing problem. In the standard cosmological model with zero or near-zero net lepton numbers, one would expect that matter-suppressed neutrino oscillations in the active neutrino or antineutrino channel proceeding in the regime above weak interaction decoupling would efficiently populate seas of singlet neutrinos. The significant additional energy density in these sterile neutrino seas would engender a faster expansion rate for the universe and a consequently higher temperature for Weak Freeze-Out. A higher Weak Freeze-Out temperature would result in more neutrons and, hence, a higher yield of ^{4}He.

A higher predicted abundance of ^{4}He may be in conflict (or close to being in conflict) with the observationally inferred upper limit on the primordial helium abundance [1]. Additionally, a fully populated sea of sterile neutrinos and antineutrinos with large rest masses could be in conflict with neutrino mass bounds derived from Cosmic Microwave Background (CMB) anisotropy limits and large-scale structure considerations.

Should we someday be confronted with a positive indication of neutrino flavor mixing with mass-squared scale consistent with the range for δm^2_{as}, we will have a problem that would call for modification either of our notions of basic neutrino physics or of the standard cosmological model. There have been a number of ways proposed to get out of these cosmological problems. Chief among these is the invocation of a significant net lepton number in the universe [2]. The idea is that the net lepton number gives active neutrinos larger effective masses in medium in the early universe, thereby driving them further off-resonance in the epoch prior to weak decoupling and reducing their effective matter mixing angles with the singlet neutrino. In turn, smaller effective matter mixing angles would imply a suppressed production of singlet neutrinos and, hence, a reduced population of the singlet neutrino sea.

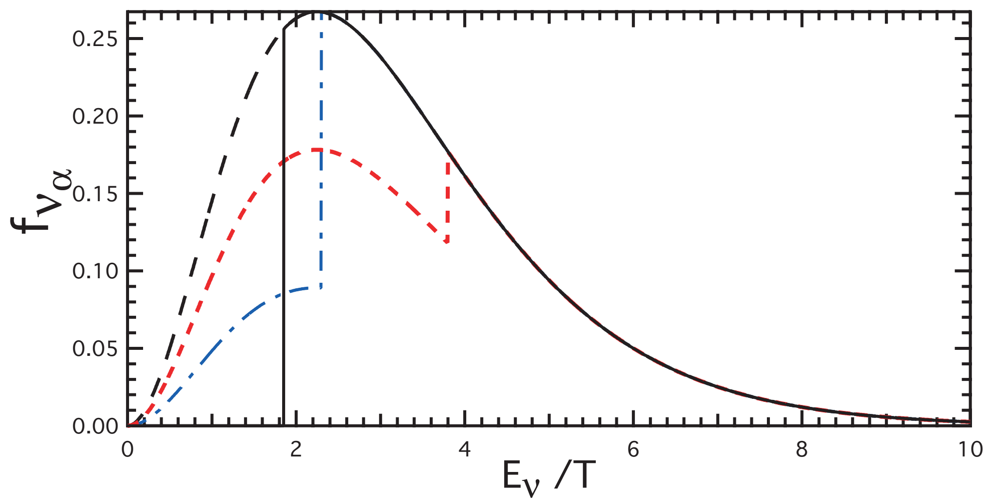

Figure 1— ***Final active neutrino energy distribution function $f_{\nu\alpha}$ for three different cases (dashed, short dashed line, and dot-dash lines) in the instantaneous active-active mixing limit as described in [3]. Here $\alpha = e,\mu,\tau$: all species have the same distribution function. The long-dash line shows the original thermal distribution function common to all active neutrino flavors.***

In [3], we study post weak decoupling coherent active-sterile and active-active matter-enhanced neutrino flavor conversion in the early universe. Under some circumstances sterile neutrino production via these processes can leave the active neutrinos with nonthermal energy spectra. In turn, these distorted energy spectra can affect primordial nucleosynthesis by altering the neutron-to-proton ratio. An example of the distorted neutrino spectra is shown in Fig. 1. Inclusion of this effect changes the relationship between the cosmological lepton numbers and the primordial ^{4}He yield and reduces the range of lepton numbers that could reconcile the observationally inferred primordial helium abundance with active-sterile vacuum neutrino mixing in the mass-squared difference range δm^2_{as}.

The existence of one or more light sterile neutrinos could alter the relationship between neutrino chemical potential and primordial nucleosynthesis yields. An ancillary conclusion is that it may not always be true that invocation of a net lepton number can reconcile an LSND-inspired light sterile neutrino with BBN limits. A lepton number with a specific magnitude will certainly suppress sterile neutrino production for epochs with temperatures above that of Weak Decoupling but at the price of driving coherent active-to-sterile neutrino conversion in the regime below Weak Decoupling.

Simplistic limits on sterile neutrinos based on *conventional* BBN calculations with thermal lepton energy distribution functions are now suspect. If the mini-BooNE experiment sees evidence for neutrino mixing in the LSND range or beyond we will be forced to re-think the BBN paradigm, incorporating the effects pointed out here.

This would also force us to confront the problem posed in [3]. Namely, what are the light element primordial nucleosynthesis abundance yields when both active-active and active-sterile neutrino inter-conversion/mixing among eight neutrino species is followed simultaneously and consistently with lepton capture/decay and nuclear reactions? This is a challenging problem at present that pushes the limits of our understanding of neutrino physics and neutrino flavor conversion in dense and hot environments.

[1] K.N. Abazajian, “Telling Three from Four Neutrinos with Cosmology,” *Astropart. Phys.* **19**, 303 (2003) [arXiv:astro-ph/0205238].
[2] R. Foot and R.R. Volkas, “Reconciling Sterile Neutrinos with Big Bang Nucleosynthesis,” *Phys. Rev. Lett.* **75**, 4350 (1995) [arXiv:hep-ph/9508275].
[3] K. Abazajian, N.F. Bell, G.M. Fuller, and Y.Y.Y. Wong, “Cosmological Lepton Asymmetry, Primordial Nucleosynthesis, and Sterile Neutrinos,” Los Alamos National Laboratory report LA-UR-04-2260 (2004) [arXiv:astro-ph/0410175].

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